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Beyond the dualism between domain-general and domain-specific abilities: a developmental approach to mathematical learning

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Understanding how cognitive abilities support mathematical learning across development remains a central question in psychology. Traditionally, scietific literature has distinguished between domain-specific abilities, referring to processes specifically involved in quantity/numerical processing and supported by systems such as the Approximate Number System (ANS) and the Object Tracking System (OTS), and domain-general abilities, which encompass broader cognitive resources such as working memory and executive functions. This paper proposes a developmental and dynamic framework that integrates previous theoretical perspectives and extends them to the earliest stages of life, suggesting that early learning may rely primarily on mechanisms dedicated to numerical understanding, whereas with age and schooling, broader cognitive resources gradually become more influential in supporting complex mathematical reasoning.

KEYWORDS

approximate number system, domain-general abilities, domain-specific abilities, numerical cognition, object tracking system

1 Introduction

Mathematical proficiency is fundamental for success in modern societies. Competence in arithmetic and calculation has been consistently linked to better employment prospects (Parsons and Bynner, 2005), higher income levels (Dougherty, 2003), effective financial decision-making (Gerardi et al., 2013), and overall life satisfaction (Carpentieri et al., 2009). From early childhood, numerical skills stand out as among the strongest predictors of later academic achievement and socioeconomic attainment (Duncan et al., 2007). Conversely, persistent difficulties in mathematics pose a serious barrier to learning, being associated with increased risk of academic failure, unemployment, and poorer psychological wellbeing (Parsons and Bynner, 2005). These concerns have gained growing attention as mathematical learning difficulties are increasingly common in school-aged populations, with recent estimates indicating that approximately 4% of children meet diagnostic criteria for developmental dyscalculia, a specific learning disorder affecting the acquisition of mathematical and calculation skills (Moll et al., 2014). To understand why some children develop such persistent difficulties, it is essential to consider how mathematical competence emerges from the interaction of multiple cognitive abilities over time. The acquisition of mathematical competence is a complex developmental process supported by multiple cognitive abilities that interact and change over time. Over the past decades, scientific literature has converged on a distinction between *domain-specific* and *domain-general* abilities, both of which seem to contribute to mathematical learning (see e.g., Coolen et al., 2021).

2 Domain-specific and domain-general abilities in mathematical learning

2.1 Domain-specific abilities: evidence for early numerical systems

Domain-specific abilities refer to cognitive processes that are tightly linked to numerical and quantitative content. These abilities can be considered "building blocks" of numerical cognition and are found to be predictors of later mathematical achievement (Feigenson et al., 2004). One relevant system that has been extensively studied is the so-called "Approximate Number System" (or ANS), which supports the approximate representation of large quantities (Dehaene, 1997). This system develops from the first hours of life until childhood to adulthood. This system is ratio-dependent since the minimal discriminable ratio passes from 1:3 in human newborns to 1:2 at 6 months to 2:3 at 9 months (Izard et al., 2009; Libertus and Brannon, 2010). Meta-analytic and longitudinal studies have found reliable associations between non-symbolic and symbolic numerical abilities. For instance, higher early ANS acuity has been found to correlate with better performance in symbolic number tasks and early counting skills (Decarli et al., 2023b; Starr et al., 2013) and some studies found that better ANS acuity in school-aged children and preschoolers was correlated with math performance (see Chen and Li, 2014 and Schneider et al., 2017 for meta-analysis; see also Amland et al., 2025, for weak associations between non-symbolic acuity and arithmetic outcomes). Importantly, studies reporting these associations have typically included control measures to ensure that the link between ANS acuity and mathematical performance was not driven by broader domain-general abilities. Tasks assessing non-numerical perceptual discrimination, general intelligence, working memory or executive functions were administered to rule out the possibility that general perceptual or executive processes account for the observed relations (e.g., Halberda et al., 2008; Wang et al., 2017; Starr et al., 2013). At the same time, several methodological challenges can affect the assessment of domain-specific abilities, particularly in young children, as highlighted by recent reviews (Krajcsi et al., 2024; De Smedt, 2022). Therefore, findings based on these measures should be interpreted with these methodological considerations in mind.

Some authors have proposed explanations for the link between early non-symbolic representations and later mathematical skills. Specifically, children may rely on approximate magnitude representations when beginning to understand the meaning of number words or digits. In this view, symbolic numbers might be gradually mapped onto pre-existing non-symbolic magnitudes, and difficulties in forming these mappings could influence the development of symbolic number knowledge (for an extensive discussion of the ANS–math link, see Libertus, 2015). Consistent with this possibility, Wong et al. (2016) investigated whether the relation between ANS acuity and symbolic arithmetic skills could be explained by children's ability to map number symbols onto approximate magnitudes. The authors tested a sample of kindergarteners and the results indicated that mapping accuracy fully accounted for the association ANS-arithmetic skills, suggesting that children who represented quantities more precisely formed more accurate symbol–quantity links during number learning. The authors interpreted this pattern as consistent with the idea that symbolic numbers become meaningful to the extent that they are successfully connected to the underlying magnitude representations (Wong et al., 2016). At the same time, several authors have proposed that symbolic numerical abilities may also exert an influence on non-symbolic magnitude processing. Behavioral studies have shown that children's symbolic magnitude skills can predict later performance on non-symbolic tasks, suggesting that experience with symbolic numbers may refine or reshape underlying magnitude representations (Matejko and Ansari, 2016; Lau et al., 2021). These findings indicate that the relation between symbolic and non-symbolic processing may not be unidirectional, and that symbolic knowledge can also contribute to changes in non-symbolic sensitivity (Piazza et al., 2013). This system has also been the focus of extensive research in atypical development, as deficits in ANS acuity have been reported in children with developmental dyscalculia: several studies have shown that children with dyscalculia exhibit impaired precision in approximate number processing compared to typically developing peers (Decarli et al., 2023a; Mazzocco et al., 2008; Piazza et al., 2010; Dolfi et al., 2024; but see also Szücs and Myers, 2017, for a critical review of training studies aimed at increasing ANS acuity). Several mechanisms have been proposed to explain how early non-symbolic representations support, or fail to support, the development of symbolic number skills. The *defective number module hypothesis* argues that some children have a fundamental difficulty in representing quantities, reflecting an imprecise or atypical magnitude system (Butterworth, 2005; see also Wilson and Dehaene, 2007). This view proposes that symbolic number learning builds directly on the precision of these non-symbolic representations; therefore, a degraded magnitude system would limit later number and arithmetic development. In contrast, *the access deficit account* suggests that the core difficulty does not lie in the representation of non-symbolic magnitudes *per se* but in the ability to access these representations from symbolic inputs (Rousselle and Noël, 2007). According to this view, children may possess relatively intact non-symbolic magnitude representations yet struggle to retrieve quantity information when presented with number words or Arabic digits. This distinction has been central in developmental work (e.g., Rousselle and Noël, 2007; De Smedt and Gilmore, 2011) and highlights that symbolic number learning requires a mapping mechanism linking symbols to underlying quantity representations.

In addition to the ANS, a second system proposed to underlie early numerical representations is the Object Tracking System (OTS). Unlike the ANS, which provides approximate representations of large quantities, the OTS supports the exact representation of small sets of discrete objects, typically up to three or four items (Feigenson et al., 2004). From the first months of life, infants are able to discriminate between small quantities—such as one vs. two or two vs. three—but their accuracy declines when set sizes exceed the limited capacity of this system (Feigenson et al., 2002; Cordes and Brannon, 2008). This mechanism underlies the phenomenon of *subitizing*, the rapid and accurate enumeration of small quantities. Both children and adults show near-perfect accuracy when identifying sets within the OTS range, while performance slows and becomes error-prone for larger numerosities. Importantly, recent developmental research has shown that children's efficiency in recognizing and labeling small exact quantities during the preschool years predicts later numerical and arithmetic skills (LeFevre et al., 2022). However, the measure used in this study involved a naming task, which requires children to verbally label small sets. As a result, the relation observed by LeFevre et al. (2022) may reflect different processes than those assessed in infancy through non-verbal paradigms (i.e., habituation and choice tasks; see Feigenson et al., 2002; Xu and Spelke, 2000).

Evidence from atypical development further highlights the role of the OTS in mathematical learning. Children with developmental dyscalculia often exhibit reduced subitizing range or slower responses when identifying small quantities, suggesting difficulties in representing exact numerosities (Ashkenazi et al., 2013; Schleifer and Landerl, 2011). Taken together, these findings suggest that both the ANS and OTS may play a fundamental role in supporting the acquisition of mathematics. However, mathematics also encompasses more complex operations that are likely to rely on the interaction of multiple cognitive systems.

2.2 Domain-general abilities: cognitive resources supporting math learning

In parallel with domain-specific theories, accumulating evidence indicates that mathematical development is not sustained solely by systems specialized in numerical processing. Broader cognitive resources play an essential role in supporting increasingly complex operations. Among these, working memory has consistently been associated with mathematical performance, as it allows children to temporarily hold and manipulate numerical information during tasks such as counting, mental arithmetic, and multi-digit calculations (Bull and Sherif, 2001; see for a review, Peng et al., 2016). Deficits in visuospatial working memory are frequently reported in children with developmental dyscalculia (Rotzer et al., 2009; Schuchardt et al., 2008), suggesting that reduced memory capacity may substantially contribute to mathematical learning difficulties. More generally, executive functions, including inhibition, cognitive flexibility, and attentional control, also play a critical role in early mathematical development. As shown by Coolen et al. (2021), executive functions were found to be a strong predictor of symbolic numerical competence and of subsequent gains in mathematical competence, highlighting their relevant role for learning. In addition to these domain-general processes, a body of research has highlighted the important contribution of language skills to mathematics (see e.g., Chow and Ekholm, 2019). This domain-general component was incorporated in the *Triple Code Model* (Dehaene and Cohen, 1996; Dehaene, 2002), which includes the role of the verbal code in number-word processing and arithmetic fact retrieval, and in developmental accounts positing that linguistic, spatial, and quantitative pathways distinctly support mathematical learning (LeFevre et al., 2010). Moreover, recent meta-analytic evidence suggests that the influence of language is most evident in complex and demanding mathematical tasks, with language comprehension playing a particularly relevant role in problem solving (Amland et al., 2025).

Together, these findings underscore the importance of considering both early number-specific systems and broader domain-general mechanisms in explaining individual differences in mathematical learning (for a review of meta-analyses on the contribution of domain-specific and domain-general factors, see De Smedt, 2022).

3 Theoretical perspectives on the interaction between domain-general and domain-specific abilities

A central question in this field concerns how domain-general cognitive abilities and domain-specific skills interact to shape learning outcomes in mathematics. Conventional theories and much of the earlier research on the relation between cognitive abilities and academic achievement have assumed a unidirectional structure, that is, cognitive abilities are seen as foundational constructs that determine performance across academic domains. Within this view, cognitive processes are thought to allow the acquisition of academic achievements, but not to be influenced by them. This assumption is exemplified by some classical accounts and, specifically, *the investment theory* (Cattell, 1987) and the *dual process theory* (Evans and Stanovich, 2013; see Peng and Kievit, 2020 for a review of these theoretical approaches). According to the *investment theory*, academic performance arises from the investment of cognitive abilities into learning opportunities provided by the environment (for instance, through schooling, social interaction, or other forms of educational stimulation), leading to the acquisition of domain-specific knowledge and skills. Similarly, the *dual process theory* posits that people rely on two complementary modes of processing. When dealing with familiar or well-practiced information, they operate in a mode that functions efficiently and demands few cognitive resources. In contrast, when they encounter novel or complex information, processing becomes controlled and effortful, drawing heavily on working memory and executive functions (Evans and Stanovich, 2013). Consequently, the degree to which cognitive abilities are engaged in an academic task depends on how efficiently and automatically that task can be performed—a factor closely tied to the learner's stored knowledge and experience with it. Early in learning, academic activities require substantial cognitive effort and attentional control; as knowledge accumulates and procedures become more familiar, performance becomes increasingly automatized, relying more on direct retrieval from long-term memory and less on domain-general cognitive control.

Recent theoretical models however have moved beyond these traditional accounts to emphasize the mutual influences between the cognitive abilities and academic performance. In particular, Peng and Kievit (2020) propose the *mutualism* framework, originally theorized by van der Maas et al. (2006), and apply it to the development of academic achievement. According to this view, domain-general and domain-specific abilities influence each other reciprocally over time, such that progress in one domain fosters growth in others. Mutualism assumes that cognitive and academic skills co-develop through interaction, progressively strengthening their interconnections. In accordance with this theory, some authors have provided evidence for a bidirectional relation between these domains (e.g., executive functions and maths: Schmitt et al., 2017).

The *transactional* perspective offers another important account of the bidirectional links between cognitive abilities and academic achievement (Dickens and Flynn, 2001; Tucker-Drob et al., 2013). According to this view, genetic influences on cognitive performance are thought to increase with age because individuals actively select and create learning environments that match and reinforce their existing abilities. As a result, the mutual influence between cognition and academic achievement is moderated by contextual factors, being stronger in more advantaged socioeconomic conditions where educational opportunities are richer. Schooling provides systematic instruction and repeated practice, which not only depend on cognitive abilities but also train and strengthen them over time (Ceci and Williams, 1997; Ritchie and Tucker-Drob, 2018). Consequently, the reciprocal links between cognitive skills and academic performance tend to be most evident during the school years, when reading and mathematics are explicitly taught and extensively practiced (Peng et al., 2019). In parallel, SES-related learning experiences contribute to these dynamics: children in high-SES contexts typically have greater access to enriching cognitive and educational stimulation, whereas those in low-SES environments face fewer opportunities for such mutually reinforcing experiences (Duncan and Murnane, 2011).

Further empirical support for this perspective comes from a recent study by Miller-Cotto and Byrnes (2020), who examined a large sample of children to investigate the reciprocal relations between working memory and academic achievement in both mathematics and reading. Their analyses revealed that early gains in working memory predicted later improvements in math and reading performance, but importantly, academic progress in these domains also contributed to subsequent growth in working memory.

Additional evidence for the bidirectional relation between cognitive and academic abilities comes from the study by Coolen et al. (2021). They examined several domain-general, domain-specific and early mathematics abilities across two time points in preschool children. Their findings revealed that executive functions and early numerical abilities were strongly correlated, and both predicted growth in mathematical performance over time. However, the longitudinal analyses indicated that the predictive path from executive functions to numerical skills was stronger than the reverse, suggesting that bidirectional influences may emerge gradually as children gain more formal experience with mathematics.

4 A dynamic and developmental framework for mathematical learning

The theoretical framework outlined in this section builds upon, and extends, previous accounts that have emphasized reciprocal relations between cognitive and academic abilities, such as the mutualism (Peng and Kievit, 2020; van der Maas et al., 2006) and transactional (Dickens and Flynn, 2001; Tucker-Drob et al., 2013) models. These approaches have been instrumental in highlighting that domain-general and domain-specific processes do not operate in isolation but instead influence each other dynamically throughout development. However, most existing frameworks have focused on middle and late childhood, when formal schooling and environmental factors already play a significant role in shaping these interactions. The current account expands on these models by shifting the focus earlier in development, to the period before and around school entry, when the foundational numerical systems are already functional. In this view, both systems play a crucial role and interact with each other, but their relative importance changes across development. During the earliest stages of life, when exposure to formal education is minimal, mathematical learning is likely to rely primarily on domain-specific mechanisms such as the ANS and the OTS. This hypothesis has its roots in evidence showing both the early functionality of these systems and their strong association with emerging symbolic and counting skills. Indeed, these foundational mechanisms are already present and functional in infancy (see e.g., Feigenson et al., 2002; Libertus and Brannon, 2010). Moreover, both systems have been found to be linked to later symbolic and counting abilities (Starr et al., 2013; Decarli et al., 2023b; LeFevre et al., 2022). Specifically, the ANS has been identified as a unique predictor of later symbolic number understanding, even when controlling for domain-general abilities (Decarli et al., 2023b; Starr et al., 2013). In Starr et al. (2013), the predictive relation between infants' non-symbolic numerical preferences and later math skills remained significant after controlling for general intelligence and for performance on a non-numerical perceptual discrimination task. Similarly, Decarli et al. (2023b) replicated and extended these findings by showing that ANS sensitivity at 12 months predicted mathematical outcomes at age four even when inhibitory control, IQ, and a face-processing perceptual control task were included in the model. These findings strengthen the view that early numerical processing is not merely a by-product of broader cognitive functions but may represent a specific and independent foundation for later mathematical learning.

One possibility to explain the link between ANS-math, is that this system could provide the representational link between non-symbolic and symbolic quantities, enabling children to associate approximate magnitudes with symbolic formats (see Wong et al., 2016). In contrast, the OTS is likely to support the identification and representation of small exact quantities, forming the basis for early enumeration and counting. Together, these two systems offer complementary mechanisms for representing both approximate and exact numerosity, laying the groundwork for the acquisition of formal mathematical concepts (see Butterworth, 2018; Piazza, 2010). The emphasis placed on the ANS and the OTS in the earliest stages should not be interpreted as assigning these systems a unique causal role. Rather, their prominence in early development reflects the current state of the empirical literature, as both systems appear to be functional from the first months of life and have been linked to the earliest forms of numerical acquisition.

As development progresses and children begin formal schooling, the demands of mathematics increase, requiring greater cognitive control, working memory, and executive functioning. At this stage, domain-general abilities are expected to play an increasingly central role, supporting the manipulation of symbols, the coordination of multiple steps in problem solving, and the integration of conceptual and procedural knowledge. In this sense, domain-specific systems may provide the initial scaffolding for numerical understanding, whereas the mastery of more complex mathematical operations likely emerges from their interaction with domain-general resources, which enables reasoning, abstraction, and flexible application of knowledge.

Further support for this developmental account comes from preliminary findings from a recent study (Decarli and Franchin, in prep.) that examined the contribution of domain-specific and domain-general abilities to mathematics performance across development. The study involved a sample of children attending the first, second, and third grades of primary school. Participants completed a battery of tasks including symbolic and non-symbolic comparison, a Go/No-Go task for inhibitory control, a short-term memory task, an access-to-numerosity task, and a standardized mathematics test covering counting, arithmetic, and magnitude reasoning. Results revealed that the pattern of correlations between mathematical performance and cognitive measures varied across age groups. Notably, non-symbolic comparison performance, reflecting ANS sensitivity, was the strongest predictor of mathematics outcomes only at school entry, while at later ages, domain-general abilities such as short-term memory and inhibitory control accounted for an increasing proportion of the variance in math performance. These results illustrate a developmental shift in the relative contribution of domain-specific and domain-general abilities, suggesting that basic numerical systems may play a predominant role in the earliest stages of mathematical learning, whereas broader cognitive processes become increasingly influential as mathematical tasks grow in complexity.

To determine the specific contribution of each ability in the process of early numerical and mathematical learning, further research is needed on domain-general skills in infancy and on how they relate to emerging mathematical competencies, especially given the current lack of longitudinal data starting from the first months of life. For example, it remains unknown whether early abilities of working memory, inhibitory control, and/or attentional processes are directly associated with infants' first numerical acquisitions, or whether these abilities might mediate the relation often observed between non-symbolic sensitivity and early counting skills. A clearer understanding of these potential pathways would provide important insights into how broader cognitive mechanisms can support the emergence of early mathematical concepts. Indeed, previous studies have typically assessed these abilities in a fragmented manner rather than adopting an integrated approach to investigate domain-specific and domain-general abilities simultaneously during the first months of life. Future longitudinal studies should therefore aim to capture these mechanisms within the very first stages of life, adopting multi-component approaches that can clarify the relative weight and interaction of domain-specific and domain-general abilities in shaping early mathematical understanding.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GD: Conceptualization, Writing – review & editing, Writing – original draft, Supervision.

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